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Title

Engagement techniques and playing level impact the biomechanical demands on rugby forwards during machine-based scrummaging

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Contributorship Statement

Ezio Preatoni: contributed to the definition of the experimental protocol and to its implementation; contributed to the design of the data collection equipment and to its validation; designed data collection software; contributed to data collection for the whole experimental campaign; designed data processing software; processed data; contributed to statistical analysis design; carried out statistical analysis; contributed to data analyses and interpretation; drafted the paper; contributed to revising the paper; approved the final version of the paper.

Keith Stokes: initiated the project; contributed to the definition of the experimental protocol and to its implementation; contributed to data collection; contributed to statistical analysis design; contributed to data interpretation; contributed to revising the paper; approved the final version of the paper.

Mike England: contributed to the definition of the experimental protocol; contributed to data interpretation; contributed to revising the paper; approved the final version of the paper.

Grant Trewartha: is guarantor. Initiated the project and supervised all its phases; contributed to the definition of the experimental protocol and to its implementation; contributed to the design of the data collection equipment and to its validation; contributed to data collection for the whole experimental campaign; contributed to statistical analysis design; contributed to data analyses and interpretation; contributed to revising the paper; approved the final version of the paper.

Andreas Wallbaum: contributed to the design and implementation of all the technical devices used in the study; contributed to data collection for the whole experimental campaign.

Nicholas Gathercole and Stephen Coombs: contributed to instrumenting and validating the scrum machine used in the study.

What are the new findings

- The characteristics and magnitude of the mechanical stresses on front-row players in the scrum have the potential to produce repetitive sub-critical injuries that could lead to chronic pain and early degenerative changes to the cervical and lumbar spine.
- Modified engagement techniques where the initial impact is de-emphasized significantly reduce the mechanical stresses acting on front-row players, irrespective of playing standard
- Reducing the dynamics of the initial engagement does not decrease the ability to generate forward sustained forces
- Forces in different playing levels vary as a factor of anthropometrics and technique, with International and Elite packs generally showing greater magnitudes and a more "dynamic" engagement phase

How might it impact on clinical practice in the near future

- Inform physicians about the mechanical loads experienced by players during contemporary rugby union scrummaging
- Provide data supporting further exploration of altered scrum engagement techniques to modify the loads experienced by players during the initial engagement phase
- Give information to assist sport physicians and rugby administrators aiming for best practices for injury prevention in rugby union

ABSTRACT

Objectives: This cross-sectional study investigated the factors that may influence the physical loading on rugby forwards performing a scrum by studying the biomechanics of machine-based scrummaging under different engagement techniques and playing levels.

Methods: Thirty-four forward packs from six playing levels performed repetitions of five different types of engagement technique against an instrumented scrum machine under realistic training conditions. Applied forces and body movements were recorded in three orthogonal directions.

Results: The modification of the engagement technique altered the load acting on players. These changes were in a similar direction and of similar magnitude irrespective of the playing level. Reducing the dynamics of the initial engagement through a fold-in procedure decreased the peak compression force, the peak downward force and the engagement speed in excess of 30%. For example, peak compression (horizontal) forces in the professional teams changed from 16.5 kN (baseline technique) to 8.6 kN (fold-in procedure). The fold-in technique also reduced the occurrence of combined high forces and head-trunk misalignment during the absorption of the impact, which was used as a measure of potential hazard, by more than 30%. Reducing the initial impact did not decrease the ability of the teams to produce sustained compression forces.

Conclusions: De-emphasizing the initial impact against the scrum machine decreased the mechanical stresses acting on forward players and may benefit players' welfare by reducing the hazard factors that may induce chronic degeneration of the spine.

INTRODUCTION

Scrummaging is a characteristic feature of rugby union. During a scrum, eight players (the forward pack) from each team bind together in three rows (front, second and back), and then bind with an opposition forward pack to compete for possession of the ball by exerting a coordinated pushing action. The purpose of the scrum is “to restart play quickly, safely and fairly, after a minor infringement or a stoppage” [1]. However, contemporary rugby union scrummaging has evolved to include a very dynamic (impact) phase during the initial engagement. Although the proportion of scrum-related injuries is relatively small at less than 8% of all rugby union injuries [2-6], scrummaging is associated with the highest propensity (risk per event) for injury and the worst severity of injuries (days lost per event) of all contact events in elite rugby [7]. The scrum is also associated with 40% of all catastrophic injuries in rugby union [8-10], and although these are rare occurrences [9,11-14] they cause irreparable impairments and tragic consequences in the player’s life. Furthermore, it has been hypothesised that, even in the absence of acute injuries, the repetitive mechanical stresses acting on players’ musculo-skeletal structures may induce soft tissue degeneration and hence chronic pain and overuse pathologies, particularly in the cervical spine [15-22]. Therefore attention must be given not only to match events, but also to training practices, which typically include repetitive scrummaging between two packs or, often, of one pack against a scrum machine (Figure 1).

**** Figure 1 here ****

Very few studies [16,23-26] have thoroughly quantified the stresses acting on forwards during a scrum, and addressed players’ safety from a biomechanical point of view. Those studies that have been performed have a number of limitations due to, in various degrees, the lack of ecological validity of their experimental set-up, the evolution of measurement techniques and technologies, and changes in the laws, playing styles and player anthropometrics that have occurred over the years [27,28]. We recently analysed the effect of playing level on the kinetics of scrummaging in a set-up that realistically mimicked typical scrum machine-based training conditions [26,29]. We identified a considerable magnitude of peak compression forces acting on the front row during scrummaging, spanning between 16.5 and 8.7 kN as a function of the playing level. We also found that the absorption of the initial impact is characterised by forces in the vertical and lateral direction that, coupled with the intense pushing action and the multiple players' interactions and movements in the three planes of motion, may destabilise the scrum [24,26].

A lively debate about opportunities for modifying the scrum engagement to make it more controlled and ostensibly safer has emerged over recent years. The aim of this paper was to: (1) assess the effects of different engagement techniques and playing levels on the biomechanical demands on players during machine scrummaging; and, (2) identify what scrummaging conditions or practices will improve forwards' safety and welfare at any playing level. The hypothesis was that de-emphasising the initial engagement velocity could reduce the magnitude of stresses absorbed by the front rows, without compromising the ability of the pack to generate forward force during the following sustained push phase.

METHODS

A cross-sectional design was used to study the effect of engagement technique (within-group factor) and playing level (between-group factor) on a set of biomechanical measures (each one representing a dependent variable) in machine-based scrummaging. The tests replicated authentic scrum-machine training sessions and were performed outdoors on natural turf.

Participants

Forward packs from thirty-four teams volunteered to take part in the research. Each pack was assigned to one of six playing categories based on competition level (Table 1). Each player provided written informed consent before participation, and the research was approved by the Institutional Ethics Committee of the University of Bath.

Table 1. Forward packs subdivision and average pack weight.

Category	Competing Level (number of teams)	Pack Weight(*)
International	6 Nations (4), RFU Premiership with international players in the pack (2)	8749 (165)
Elite	Pro 12 (3), RFU Premiership (2), RFU Championship (1)	8523 (143)
Community	RFU Level 5-7 (6)	8262 (325)
Academy	Pro 12 Academy (1), RFU Premiership Academy (1), RFU Championship Academy (1), British Universities (3)	7771 (197)
Women	6 Nations (2), RFU Premiership (1), RFU Championship (1)	6326 (257)
School	RFU Level 7 Colts & U17 (2), Pro 12 U18 (2), National Schools U18 Cup (2)	6685 (637)

(*)= mean (standard deviation). Weight is reported in N.

Data Collection

Following a standard warm-up, the pack performed a set of four to eight scrums for each of the five different engagement techniques considered. These included (Table 2) the current scrummaging practice at the initiation of the study ("Crouch-Touch-Pause-Engage"), taken as the baseline condition, and four modified techniques that differed from the baseline only in the referee's calls (i.e. the three-stage sequence introduced by the IRB for the 2012-13 season as a law amendment trial) or in technique changes designed in part to modify the loading conditions on the front row at the initiation of the engagement (i.e. by substituting the initial impact with a fold-in procedure or by asking the back row to engage sequentially). At least one and five minute rest was allowed between repetitions and sets, respectively, to avoid fatigue. A maximum of 24 scrums were completed in any one testing session so some teams completed trials over two testing occasions. The sets of different conditions were executed in random order.

Table 2. Description of the different engagement techniques analysed.

Condition	Abbreviation	Referee's calls	Description
Hit & Hold	CTPE	crouch–touch–pause–engage	Baseline condition. The forward pack engaged the machine and held a short-duration sustained push.
3-Stage	CTS	crouch–touch–x[(*)]–set	Similarly to CTPE in motion but the vocal engagement sequence was modified by substituting the "pause" call with a non-verbal pause.
Fold-In	Fold-in	crouch–touch–pause–engage–shape–power	Following the CTPE engagement sequence the forward pack had already received instructions to engage the machine with no attempt to generate momentum before contact with the pads (i.e. to "fold-in"). Following a short period of settling the pack received a verbal instruction to adopt good body posture ("shape") and then a further verbal command to initiate a push ("power") which was maintained for a short duration.
Sequential, 7+1	7+1	crouch–touch–pause–engage	Player number 8 was instructed to have no involvement in the initial engagement phase. The front 7 players went through the CTPE engagement sequence and hold of the push. Having allowed the initial engagement to occur the number 8 could then find a binding position between the second row forwards and contribute to the push already taking place.
Sequential, 5+3	5+3	crouch–touch–pause–engage	The entire back row (number 8 and flankers) were instructed to have no involvement in the initial engagement phase. The front 5 players went through the CTPE engagement sequence and hold of the push. Having allowed the initial engagement to occur the back row could then find their normal binding position ("latch on") and contribute to the push already taking place.

[(*)] x= non-verbal pause.

Instrumentation and Data Processing

A bespoke control and acquisition system (cRIO-9024, National Instruments, Austin, USA) programmed in Labview (v2010, National Instruments, Austin, USA) was devised to synchronously: (1) play pre-recorded audio files that simulated the referee's commands with consistent timing (Table 2); (2) trigger the digital video cameras that operated at 50 Hz and recorded players' movements from three different views (left, top and right, Figure 1); and, (3) excite strain-gauge force transducers placed on each of the four beams of a commercially available sled-type scrum machine (Dictator, Rhino Rugby, Rooksbridge, UK) and acquire compression, lateral and vertical force signals at a frequency of 500 Hz. All the measuring devices were calibrated prior to testing and their local reference frame was transformed to a common one where x was the lateral (positive to the right), y the longitudinal (positive forward/compression) and z the vertical (positive upward) direction (Figure 1). A more detailed description of the instrumentation, of calibrations and measuring procedures, and of their reliability can be found in previously published articles [26,29].

Custom-made Matlab functions (Matlab R2010b, MatWorks, Natick, USA) were written to process data and calculate a set of more than 1000 parameters from force (195) and motion (990) variables from each available trial, condition and team. For the purposes of this paper, a subset of these measures (Table 3 and Figure 2) was selected to analyse the mechanics of pack-machine interaction from the initial set-up, through the engagement phase (i.e. from the onset of contact forces to the establishment of a steady-state force), to the sustained push phase [26,29].

Statistics

Average measures from individual teams were used to characterise groups through descriptive statistics. Mixed design ANOVA were carried out to assess the significance ($P<0.05$) of main effects between and within groups, and of the playing level-engagement technique interaction. Bonferroni tests were used in the post-hoc analysis of main effects, and effect sizes (partial eta-squared, η^2) and observed power (OP) were included in the analysis. Pairwise effect sizes (Cohen's d) [30] between engagement techniques were also considered.

**** Figure 2 here ****

Table 3. Description of analysed measures. Please refer to Figure 2 for an annotated graphical representation of force parameters/phases.

Parameter	Phase	Description
Motions		
Distance from the pads	Set-up	Distance between the front row players C7 and the scrum machine pads at the onset of movement.
Maximum engagement speed	Engagement	Front row centre of mass maximum velocity during the initial engagement phase. The front row centre of mass has been defined as the weighted average of the centres of mass of the trunk of the three front row players.
Forces		
Peak compression force	Engagement	Maximum of the compression force during engagement.
Positive forward impulse	Engagement	Area under the compression force curve, calculated between the time of engagement and the instant when the force drops down to the value of the sustained push.
Negative forward impulse	Engagement	Area between the level of average sustained push and the compression force curve, calculated from the end of the positive impulse interval to the beginning of the sustained push phase
Average sustained push	Sustained push	Average value of the compression force over the sustained push phase.
Peak vertical force	Engagement	Peak vertical force during engagement (always downward / negative).
Average sustained vertical force	Sustained push	Average value of the vertical push over a 1 s interval from the end of engagement.
Range of lateral force	Engagement	Range of lateral forces during engagement.
Average sustained lateral force	Sustained push	Average value of the lateral push over a 1 s interval from the end of engagement.
Integrated		
Hazard Index	Engagement	Based on the ‘spine in line’ principle and on the assumption that potential risk for the upper spine may come from the concurrency of high forces and increased neck angles. The Hazard Index (*HI*) is a combination of forces (typically acting through the shoulder and base of the neck) and neck deviations (i.e. absolute neck angle in the horizontal plane) averaged over the duration of the engagement phase and across the front-five players, who are the ones with spine constrained on both ends (see Supplement 2 for a detailed description). *HI* is not a validated metric but a proposed quantity which includes kinematic and kinetic factors likely related to the generation of undesired stresses on the spine (e.g. bending in compression). *HI* varies between 0 and 1, where the higher the value, the higher the average hazard on the front five forwards. In addition, forces and angle-deviations coupling varies throughout the engagement phase. This change can be calculated at each time, and its maximum value can be taken into account as the worst combination in terms of hazard over the engagement phase (Maximum Hazard measure).

Phases of scrummaging (see also Figure 2): engagement (i.e. interval between the onset of forces and 1 s after the peak of compression force); sustained push (i.e. 1 s interval from the end of the engagement, with the exception of Fold-in for which the last 1 s was considered). Force measures are the total force generated by the forward pack, i.e. the sum of forces measured by the four instrumented beams of the scrum machine.

RESULTS

Results are presented sequentially across the three main phases of scrummaging (Table 3 and Figure 2): set-up and onset of movement, engagement, and sustained push.

The mixed design ANOVA did not identify any interaction effects between engagement technique and playing level for any of the reported variables with the exception of maximum compression force, for which, however, the differences between engagement conditions showed very similar trends for all playing conditions (Figure 3a).

**** Figure 3 here ****

Set-up and onset of movement

The Fold-in technique on average reduced the distance from the pads by about 0.12 m ($P<0.001$, $\eta^2=0.352$, OP=1.000), and the maximum engagement speed by more than 0.86 m/s ($P<0.001$, $\eta^2=0.693$, OP=1.000) (Table 4, Figure 3b and Supplement 1).

No major differences were found between playing levels, besides Academy teams setting farther from the pads than International, and Elite teams engaging at a higher velocity than School teams (Table 4).

Table 4. Parameters during the initiation of scrummaging, across the 5 different engagement techniques and 6 different playing levels. *

Variable\Category	CTPE	CTS	Fold-in	7+1	5+3
Distance from the pads [m] $^{\dagger\#}$	^{3}	^{3}	^{1,2,4,5}	^{3}	^{3}
International ^{a}	0.39 (0.10)	0.38 (0.12)	0.33 (0.08)	0.40 (0.09)	0.38 (0.08)
Elite	0.46 (0.08)	0.44 (0.11)	0.41 (0.04)	0.45 (0.09)	0.46 (0.08)
Community	0.45 (0.08)	0.45 (0.11)	0.38 (0.11)	0.49 (0.12)	0.57 (0.12)
Academy ^{i}	0.50 (0.08)	0.52 (0.10)	0.44 (0.12)	0.52 (0.10)	0.53 (0.08)
Women	0.48 (0.03)	0.41 (0.05)	0.29 (0.03)	0.44 (0.02)	0.40 (0.05)
School	0.42 (0.06)	0.42 (0.13)	0.37 (0.09)	0.43 (0.09)	0.47 (0.10)
Maximum engagement speed [m/s] $^{\dagger\#}$	^{3}	^{3}	^{1,2,4,5}	^{3}	^{3}
International	2.7 (0.6)	2.9 (0.4)	1.8 (0.5)	2.7 (0.3)	2.7 (0.4)
Elite ^{s}	3.0 (0.6)	3.0 (0.6)	2.3 (0.2)	3.0 (0.7)	2.9 (0.6)
Community	2.9 (0.4)	2.9 (0.1)	1.7 (0.4)	2.8 (0.3)	2.6 (0.4)
Academy	2.7 (0.2)	2.5 (0.5)	1.5 (0.3)	2.6 (0.4)	2.3 (0.4)
Women	2.4 (0.4)	2.5 (0.3)	1.5 (0.1)	2.5 (0.3)	2.5 (0.3)
School ^{e}	2.3 (0.4)	2.5 (0.3)	1.4 (0.5)	2.3 (0.6)	2.4 (0.4)

* measures are reported as mean (standard deviation). Significant main effect (P<0.05) between playing levels (†) and pairwise comparisons are reported by the following convention: ^{i}= different from International; ^{e}= different from Elite; ^{c}= different from Community; ^{a}= different from Academy; ^{w}= different from Women; ^{s}= different from School. Significant main effect (P<0.05) between engagement conditions ($^{\#}$) and pairwise comparisons are reported by the following convention: ^{1}= different from CTPE; ^{2}= different from CTS; ^{3}= different from Fold-in; ^{4}= different from 7+1; ^{5}= different from 5+3.

Engagement

The Fold-in engagement technique reduced the peak compression force during the initial impact, by at least 30%, in comparison with all the other engagement techniques, and by about 50% in comparison with CTPE (P<0.001, η^2=0.889, OP=1.000) (Table 5 and Figure 3a). For example, the peak engagement force for International teams reduced from 16.5 kN in CTPE to 8.6 kN in Fold-in. The Fold-in technique caused less negative impulse ("rebound phase", P<0.001, η^2=0.405, OP=1.000), less peak downward force (P<0.001, η^2=0.349, OP=1.000), and a smaller range of lateral forces (P<0.001, η^2=0.588, OP=1.000) (Table 5 and Figure 3c,d).

Fold-in also decreased the Maximum Hazard measure (worst combination of force multiplied by neck deviation) over the engagement phase (P<0.001, η^2=0.465, OP=1.000) (Table 5 and Figure 3f). Effect sizes (Supplement 1) showed the Hazard Index (average combination of force and neck deviation) was moderately lower in Fold-in than in the CTPE and 3-Stage conditions, but confirmed very large effects for the Maximum Hazard measure, with Fold-in having lower values than all the other engagement techniques. The sequential 5+3 engagement decreased the magnitude of positive impulse ($P<0.001$, $\eta^2=0.701$, OP=1.000) and increased the magnitude of the negative impulse ($P<0.001$, $\eta^2=0.405$, OP=1.000) compared with all the other techniques.

Peak compression forces highlighted a difference between playing level groups ($P<0.001$, $\eta^2=0.813$, OP=1.000), with International and Elite reporting higher absolute values than Community and Academy, who in turn returned higher values than Women and School (significant for Community vs. Women and School, and close to being significant for Academy vs. Women, $P=0.06$, and School, $P=0.07$, Table 5). Negative impulse ($P<0.001$, $\eta^2=0.405$, OP=1.000), peak downward force ($P<0.001$, $\eta^2=0.349$, OP=1.000), range of lateral forces ($P<0.001$, $\eta^2=0.588$, OP=1.000) and maximum hazard measure ($P<0.001$, $\eta^2=0.465$, OP=1.000) tended to separate International and Elite from the other four categories, depending on the variable of interest (Table 5). Positive impulse, in contrast, reported lower values in the Women and School subgroups than in the remaining four playing standards ($P<0.001$, $\eta^2=0.701$, OP=1.000), whereas the Hazard Index did not evidence any difference across playing levels ($P=0.596$, $\eta^2=0.145$, OP=0.219).

Normalising forces to the weight of the scrum pack eradicated the differences for most of the measures related to shock absorption. International and Elite maintained higher magnitudes of peak compression forces than the other four levels ($P<0.001$, $\eta^2=0.696$, OP=1.000), larger loss of impulse than Community, Academy and School ($P=0.002$, $\eta^2=0.472$, OP=0.958), and higher range of lateral forces than Community and School ($P=0.003$, $\eta^2=0.460$, OP=0.948) (Table 5).

Table 5. Parameters during the engagement phase across the 5 different engagement techniques and 6 different playing levels. *

Variable\Category	CTPE	CTS	Fold-in	7+1	5+3
Peak compression force [kN] † #	2,3,5	1,3,5	1,2,4,5	3,5	1,2,3,4
International [c,a,w,s]	16.5 (1.4)	15.8 (1.6)	8.6 (2.0)	15.6 (1.3)	14.2 (1.6)
Elite [c,a,w,s]	16.5 (1.4)	15.9 (1.5)	8.6 (0.9)	15.8 (1.6)	14.5 (1.5)
Community [i,e,w,s]	12.0 (1.6)	11.9 (1.7)	5.9 (1.3)	11.6 (1.5)	10.0 (0.9)
Academy [i,e]	11.7 (2.0)	11.1 (1.3)	6.5 (1.2)	11.3 (1.8)	10.2 (1.6)
Women [i,e,c]	8.7 (0.1)	8.0 (0.2)	4.4 (0.4)	8.1 (0.8)	7.0 (1.0)
School [i,e,c]	9.1 (3.2)	8.7 (2.3)	4.2 (0.8)	8.6 (2.9)	7.5 (2.7)
Normalised peak compression force [multiples of pack weight] † #	2,3,4,5	1,3,5	1,2,4,5	1,3,5	1,2,3,4
International [c,a,w,s]	1.88 (0.15)	1.80 (0.18)	0.98 (0.23)	1.78 (0.14)	1.63 (0.19)
Elite [c,a,w,s]	1.94 (0.16)	1.86 (0.16)	1.01 (0.11)	1.86 (0.16)	1.69 (0.15)
Community [i,e]	1.45 (0.18)	1.44 (0.20)	0.71 (0.15)	1.40 (0.14)	1.21 (0.10)
Academy [i,e]	1.50 (0.25)	1.43 (0.17)	0.83 (0.14)	1.45 (0.21)	1.31 (0.20)
Women [i,e]	1.37 (0.07)	1.27 (0.05)	0.70 (0.09)	1.28 (0.13)	1.11 (0.17)
School [i,e]	1.34 (0.35)	1.28 (0.23)	0.62 (0.08)	1.26 (0.32)	1.10 (0.30)
Positive Impulse [kN·s] † #	3,4,5	3,4,5	1,2,5	1,2,5	1,2,3,4
International [w,s]	3.1 (0.3)	3.4 (0.6)	2.3 (1.0)	2.8 (0.3)	1.9 (0.2)
Elite [w,s]	3.3 (0.4)	3.0 (0.4)	2.7 (0.5)	2.7 (0.4)	1.9 (0.2)
Community [w,s]	3.0 (0.8)	2.9 (0.4)	2.6 (0.3)	2.3 (0.3)	1.6 (0.2)
Academy [w,s]	2.8 (0.3)	3.2 (0.5)	2.4 (0.8)	2.3 (0.3)	1.9 (0.5)
Women [i,e,c,a]	2.1 (0.1)	2.0 (0.2)	1.7 (0.2)	1.7 (0.2)	1.1 (0.1)
School [i,e,c,a]	2.2 (0.3)	2.2 (0.4)	1.4 (0.2)	1.7 (0.4)	1.1 (0.3)
Negative Impulse [kN·s] † #	3,5	3,5	1,2,4,5	3,5	1,2,3,4
International [c,a,w,s]	-1.0 (0.7)	-1.0 (0.7)	-0.3 (0.3)	-1.0 (0.7)	-1.3 (0.8)
Elite [c,a,s]	-1.1 (0.4)	-0.9 (0.3)	-0.5 (0.2)	-1.0 (0.4)	-1.2 (0.4)
Community [i,e]	-0.4 (0.2)	-0.2 (0.1)	-0.1 (0.1)	-0.4 (0.2)	-0.7 (0.4)
Academy [i,e]	-0.5 (0.2)	-0.3 (0.2)	-0.2 (0.1)	-0.5 (0.3)	-0.7 (0.3)
Women [i]	-0.4 (0.2)	-0.4 (0.1)	-0.3 (0.3)	-0.4 (0.2)	-0.7 (0.3)
School [i,e]	-0.3 (0.2)	-0.2 (0.1)	-0.3 (0.2)	-0.3 (0.1)	-0.6 (0.4)
Peak vertical force [kN] † #	3,5	3,5	1,2,4	3,5	1,2,4
International	-3.6 (1.4)	-3.8 (1.0)	-2.7 (0.9)	-3.1 (0.7)	-2.44 (0.6)
Elite [c,w,s]	-3.9 (0.7)	-4.5 (1.1)	-3.1 (0.7)	-3.9 (0.6)	-3.0 (1.1)
Community [e]	-2.3 (1.1)	-2.5 (1.1)	-1.4 (0.6)	-2.4 (0.9)	-1.6 (0.6)
Academy	-2.9 (1.1)	-3.0 (1.2)	-2.3 (0.5)	-3.3 (1.3)	-2.6 (0.8)
Women [e]	-2.4 (0.7)	-2.2 (0.9)	-1.6 (0.6)	-2.1 (1.0)	-1.7 (0.3)
School [e]	-2.0 (1.0)	-2.3 (1.3)	-1.2 (0.6)	-2.1 (1.5)	-1.9 (1.2)
Range of Lateral Force [kN] † #	3	3	1,2,4,5	3	3
International [c,a,w,s]	1.8 (0.3)	1.9 (0.3)	1.0 (0.3)	1.9 (0.5)	1.8 (0.3)
Elite [w,s]	1.7 (0.1)	1.9 (0.4)	1.2 (0.3)	1.8 (0.4)	1.6 (0.2)
Community [i]	1.5 (0.4)	1.4 (0.5)	0.7 (0.2)	1.3 (0.3)	1.3 (0.5)
Academy [i]	1.3 (0.1)	1.3 (0.2)	0.8 (0.2)	1.5 (0.2)	1.5 (0.2)
Women [i,e]	1.3 (0.3)	1.0 (0.2)	0.6 (0.1)	0.9 (0.2)	1.1 (0.1)
School [i,e]	1.1 (0.3)	1.1 (0.4)	0.6 (0.1)	1.1 (0.3)	1.0 (0.4)
Hazard Index [au]	3,5		1		1
International	0.12 (0.02)	0.12 (0.03)	0.11 (0.02)	0.12 (0.03)	0.10 (0.02)
Elite	0.16 (0.05)	0.13 (0.03)	0.13 (0.03)	0.16 (0.03)	0.14 (0.03)
Community	0.18 (0.06)	0.12 (0.06)	0.12 (0.02)	0.18 (0.09)	0.14 (0.02)
Academy	0.12 (0.03)	0.14 (0.06)	0.13 (0.03)	0.12 (0.04)	0.11 (0.02)
Women	0.15 (0.02)	0.15 (0.03)	0.11 (0.06)	0.12 (0.01)	0.11 (0.02)
School	0.13 (0.04)	0.12 (0.06)	0.11 (0.06)	0.12 (0.05)	0.10 (0.02)
Max Hazard Measure [au] † #	3	3	1,2,4,5	3	3
International [c,a,w,s]	2807 (572)	2640 (466)	1542 (299)	2808 (688)	3059 (783)
Elite [c,a,w,s]	3431 (1010)	2655 (335)	1911 (272)	3196 (482)	2460 (347)
Community [i,e]	2851 (1008)	2269 (626)	1128 (142)	1866 (647)	1486 (203)
Academy [i,e]	2065 (275)	2225 (730)	1197 (410)	1959 (468)	2002 (256)
Women [i,e]	1754 (275)	1793 (380)	788 (107)	1523 (458)	1554 (779)
School [i,e]	1722 (624)	1520 (315)	928 (173)	1500 (638)	1404 (446)

* measures are reported as mean (standard deviation). Significant main effect (P<0.05) between playing levels (†) and pairwise comparisons are reported by the following convention: ^{i}= different from International; ^{e}= different from Elite; ^{c}= different from Community; ^{a}= different from Academy; ^{w}= different from Women; ^{s}= different from School. Significant main effect (P<0.05) between engagement conditions ($^{\#}$) and pairwise comparisons are reported by the following convention: ^{1}= different from CTPE; ^{2}= different from CTS; ^{3}= different from Fold-in; ^{4}= different from 7+1; ^{5}= different from 5+3.

Sustained push

Sustained compression forces were greater for International and Elite in both absolute and normalised force values. The Fold-in engagement produced higher sustained compression force than the other conditions. This difference was significant (P<0.001, η^2=0.225, OP=0.998) in comparison with 3-Stage and 5+3, but also showed moderate effect sizes with CTPE and 7+1 (Table 6, Figure 3e and Supplement 1). There was a more upward sustained push force in the Fold-in technique than in the other conditions (P<0.001, η^2=0.444, OP=1.000) (Table 6 and Supplement 1), with no differences across levels. Sustained lateral push forces did not show changes across either levels or techniques.

Table 6. Parameters during the sustained push phase across the 5 different engagement techniques and 6 different playing levels. *

Variable\Category	CTPE	CTS	Fold-in	7+1	5+3
Average sustained push [kN] † #	[2]	[1,3]	[1,2]		[3]
International [c,a,w,s]	8.3 (1.0)	8.0 (1.2)	8.5 (0.9)	8.4 (0.9)	8.5 (0.7)
Elite [c,a,w,s]	7.9 (0.7)	7.9 (0.5)	8.3 (0.4)	8.0 (0.3)	7.9 (0.6)
Community [i,e]	5.8 (0.4)	5.7 (0.5)	6.2 (0.5)	5.6 (0.4)	5.8 (0.5)
Academy [i,e]	5.9 (0.8)	5.6 (0.5)	6.0 (0.6)	5.9 (0.6)	5.9 (0.8)
Women [i,e]	4.8 (0.5)	4.4 (0.2)	4.8 (0.6)	4.8 (0.6)	4.6 (0.4)
School [i,e]	4.9 (0.1)	4.5 (1.1)	5.1 (1.1)	4.8 (1.3)	4.8 (1.2)
Average sustained vertical force [kN] † #	[3]	[3]	[1,2,4,5]	[3]	[3]
International	1.1 (1.3)	1.1 (1.5)	1.5 (1.5)	1.6 (0.9)	1.3 (0.9)
Elite	0.7 (0.9)	0.2 (0.6)	2.0 (0.3)	0.9 (1.0)	1.0 (0.6)
Community	-0.0 (0.9)	0.0 (1.0)	1.3 (0.5)	-0.1 (0.7)	0.0 (0.5)
Academy	0.1 (0.6)	-0.1 (0.7)	1.0 (1.0)	-0.2 (0.4)	0.1 (0.5)
Women	0.0 (0.5)	-0.3 (0.3)	0.5 (0.6)	0.2 (0.4)	-0.1 (0.4)
School	0.1 (0.9)	-0.2 (0.6)	0.9 (0.7)	-0.0 (0.7)	0.2 (0.8)
Average sustained lateral force [kN]					
International	0.6 (0.5)	0.5 (0.7)	0.5 (0.7)	0.5 (0.7)	0.4 (0.5)
Elite	0.6 (0.4)	0.5 (0.4)	0.6 (0.4)	0.5 (0.4)	0.6 (0.5)
Community	0.1 (0.6)	0.3 (0.4)	0.4 (0.4)	0.2 (0.3)	0.2 (0.3)
Academy	0.1 (0.3)	0.1 (0.3)	0.2 (0.5)	0.2 (0.3)	0.1 (0.2)
Women	-0.1 (0.3)	-0.1 (0.2)	-0.0 (0.1)	-0.1 (0.2)	-0.0 (0.2)
School	0.1 (0.3)	0.1 (0.3)	0.1 (0.4)	-0.0 (0.2)	-0.0 (0.3)

* measures are reported as mean (standard deviation). Significant main effect (P<0.05) between playing levels (†) and pairwise comparisons are reported by the following convention: [i]= different from International; [e]= different from Elite; [c]= different from Community; [a]= different from Academy; [w]= different from Women; [s]= different from School. Significant main effect (P<0.05) between engagement conditions (#) and pairwise comparisons are reported by the following convention: [1]= different from CTPE; [2]= different from CTS; [3]= different from Fold-in; [4]= different from 7+1; [5]= different from 5+3.

DISCUSSION

The principal aim of this research was to study the effect of different engagement techniques on the biomechanical demands experienced by rugby forwards during machine-scrummaging, with a view to identifying possible hazard factors to inform the development of safer scrummaging techniques. The effect of different playing levels was also examined.

In general the substitution of a dynamic engagement with a fold-in procedure considerably reduced the impact forces in forward, lateral and vertical directions, decreased the hazard parameters that were defined in this work, and therefore indicate a potential reduction of the factors that may conceivably contribute to acute injury and overuse spinal degeneration. The differences observed between engagement techniques were in a similar direction and of similar magnitude of effect irrespective of the playing level. This is important inasmuch as it provides an indication that the introduction of any technique modification designed to alter the stresses acting on forwards during scrummaging should have the same outcome across all playing standards.

De-emphasising the initial impact against the scrum machine produced a number of significant changes in comparison with all the other techniques. Adopting a fold-in procedure in place of the conventional engagement (CTPE) made the packs set up about 15% closer to the pads and reduced the maximum engagement speed in excess of 30%. This technique ultimately attenuated the peak compression, downward and lateral forces generated against the scrum machine, and the maximum hazard measure by about 50%, 30%, 40%, and 50%, respectively. Given that the reduction of vertical and lateral forces [16,24,26] and avoidance of situations that cause sudden compression and bending have been advocated in order to minimise the likelihood of both acute injuries and chronic degeneration of the spine [31-35], the reduced forces in the Fold-in condition are likely to represent an important reduction in injury risk.

The sequential 5+3 engagement also reduced the compression and vertical forces at the initial impact, but the magnitude of this reduction was less than in Fold-in. Furthermore, asking the back-row to join the scrum only after the initial impact produced some negative effects on the stability of front-five players [36] due to the flankers having difficulty in immediately finding an effective and unobtrusive bind with the props, and to the action of the number 8 who needed to pull the lock forwards sideways to find room for his/her head. These interferences may increase the risk of a ‘buckling effect’ (i.e. mechanical instability due to concurrent bending and compression loads) on the spine of the front-five players [31-35]. This interpretation is supported by some of the engagement phase measures, whereby the range of lateral forces and the Maximum Hazard measure (i.e. worst combination of forces and neck deviations) were similar to the baseline techniques in 5+3, whereas they were lower than all other techniques in Fold-in. The 5+3 technique also showed the largest negative impulse during the rebound phase, which represents the transition from the initial contact to the final sustained push. This loss of impulse is a negative performance factor, as it is related to the ability of maintaining a forward expression of force, but may also represent an index of stability in association with lateral and vertical forces. Peaks in shear forces coupled with a loss of control over the pushing action may in fact increase the risk of scrum disruptions, when transferred into a live scrum context, due to the concurrent action of the opposing pack and the possible onset of rotational momentum on the two front-rows. Indeed, in a contested scrum the opposing forward pack cannot offer a counterbalance as steady as that provided by a static object like a scrum machine. It must be observed, however, that players were well aware they were scrummaging against a scrum machine and may have adapted their engagement strategy relying on its stable support [26].

Reducing the dynamics of the initial engagement did not decrease the ability of teams to generate forward forces during the sustained push. Although the Fold-in technique resulted in lower compression force and positive impulse during the initial engagement, the sustained push force was equal or even higher than in all the other conditions. This suggests that the generation of high pushing forces during machine scrummaging is not dependent on the intensity of the initial engagement phase and to a certain extent the engagement characteristics of the other conditions runs counter-productive to the development of high forces in the sustained phase. Therefore, going towards a conceivably safer technique should not hinder the ability of teams to generate an effective performance. However, within the scrum machine testing set-up, teams typically produced larger upward forces during the sustained phase of the Fold-in condition. It is not clear yet whether this more upward drive was a function of the scrum machine testing environment and whether or not it would carry over to live scrummaging and induce disruptions and stresses on the spine via the creation of upward rotational momentum.

This study returned higher absolute force values across all phases and across all playing levels when compared with the most widely cited previous study [24], albeit more similar to those reported in more contemporary studies [16,37]. The development of forwards' physical characteristics [27,28] together with other factors [26] such as the increase in engagement speed and the more ecological testing conditions may explain the remarkable change of peak engagement forces registered over the last two decades [16,23-26]. The differences in the absolute force values generated by different playing levels were in line with expectations, as results separated them into three main sub-groups exhibiting similar force patterns: International and Elite; Community and Academy; Women and School. Differences in absolute force magnitudes in all three directions were marked between these sub-groups, particularly during the engagement phase, with Women and School generating about 50-60%, and Community and Academy approximately 60-80% of the forces produced by International and Elite across the compression, vertical and lateral directions. However, after normalising the force measures of the dynamic phase to account for the mass of the forward pack, many of the differences between Community, Academy, Women and School playing levels disappeared. This means that some of the differences originally present between categories were simply a result of the greater mass of players. International and Elite showed higher compression peaks even after normalisation, which can be interpreted as a true ability to produce a more dynamic initial impact, relying on a better technique and/or a better physical condition. This view is supported by the fact that these two playing levels also differed from the others with a greater normalised sustained push force, which is generated under semi-static conditions and therefore cannot be influenced by inertia properties.

Determining the external biomechanical thresholds that may cause injury is difficult since it is problematic to identify both the general mechanisms causing real-world injuries and the contribution of each factor involved in their insurgence [31]. Currently, computer simulation and cadaver studies in applications relatively different from scrummaging (e.g. crash tests) are the only references available for cervical injury due to impacts [33-35,38-41]. Therefore, care should be taken in attempting to transfer findings from this domain to the rugby scrum setting, where both the physical characteristics of participants and the type of mechanical stresses applied can be sensibly observed as different [26]. Nevertheless, a general consensus has been agreed in classifying injuries to the cervical spine and in identifying their causes in the magnitude, direction and rate of load application together with the head constraints and orientation of the neck [42,43]. If the load is applied at a distance from the central axis of the spine and/or shear force components (i.e. lateral and vertical) are present, a bending action is generated. These eccentric forces may have a bearing on specific traumas, such as ligament disruptions and bilateral facet dislocations at the lower cervical column level [42], and on chronic degeneration of the spine [17,22] .

Previously published findings from our group [26] have shown that the repetitive mechanical stresses acting on players during a CTPE engagement, coupled with the constrained head and body segment motions of tight forwards (front and second row), may fall in the area indicated by some authors as potentially hazardous in terms of spinal injury mechanisms [31,33,35,41]. In particular, the type and magnitude of load on players deserves attention in relation to cervical and lumbar spine sub-critical injuries, which might initiate a vicious loop whereby degenerative changes, chronic pain and alterations to load distribution are mutually linked [17,33,35,38,39]. Results from the present study have confirmed the hypothesis that modifying the engagement technique towards a more controlled initial contact helps in considerably reducing the biomechanical demands on forwards. No evidence of proportionality between load reduction and injury risk can be put forward without a prospective epidemiological study and a thorough knowledge of the threshold above which external forces can produce an injury. However, keeping in mind all the aforementioned limitations, it is reasonable to assume that, given the magnitude of changes introduced and the repetitive nature of scrummaging, a more controlled and less dynamic initial engagement similar to the Fold-in procedure could be beneficial for the reduction of both catastrophic and overuse injuries.

It is fully acknowledged that machine scrummaging will likely have different characteristics to live contested scrummaging and so the extent to which interpretation can be made on injury mechanisms and injury risk for contested scrummaging from the current data still has to be verified. However, machine scrummaging can be considered an essential starting point for the analysis of potential injury factors because (1) it is currently a widespread training practice that involves the repetition of multiple scrums on a weekly basis, (2) it offers a more controlled setting than contested scrummaging for understanding the influence of playing level and modified engagement techniques, and, (3) it allows a comparison of measures with the ones available from the literature.

CONCLUSION

The objective of this research was to investigate modifications in the engagement technique that could contribute to players' welfare in relation to scrummaging. Overall, de-emphasizing the initial impact led to significant reductions of the mechanical stresses acting on forward players and it is conceivably a possible route to injury prevention in this relatively controllable training/match event.

We are currently undertaking further studies to transfer these findings to a contested live scrummaging context, where two forward packs are involved, and to gain more insight into how the combination of external load and body movements translate into internal stresses acting on the spine.

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COMPETING INTERESTS

None of the authors has competing financial, professional or personal interests that might have influenced the performance or presentation of the work described in this manuscript.

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FIGURE CAPTIONS

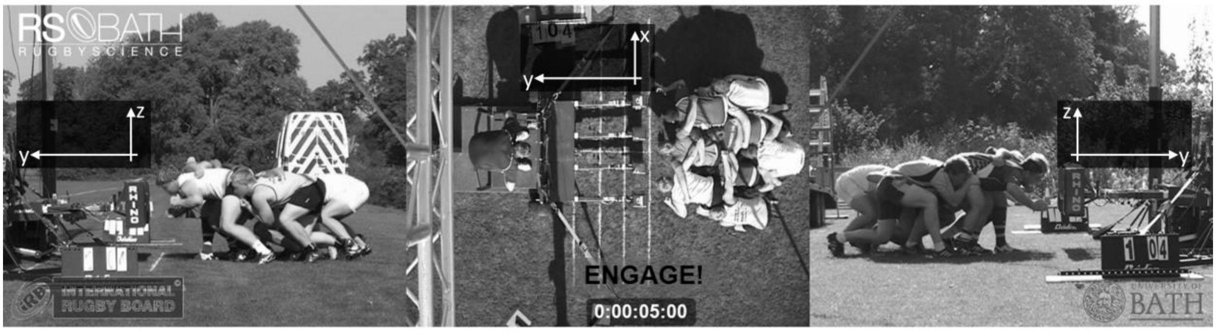

Figure 1. The experimental set-up from the three camera views (left, top, right). The instant represented is the time at the “Engage” call in a CTPE trial. The directions of the reference frame (x= lateral; y= compression; z= vertical) are also shown.

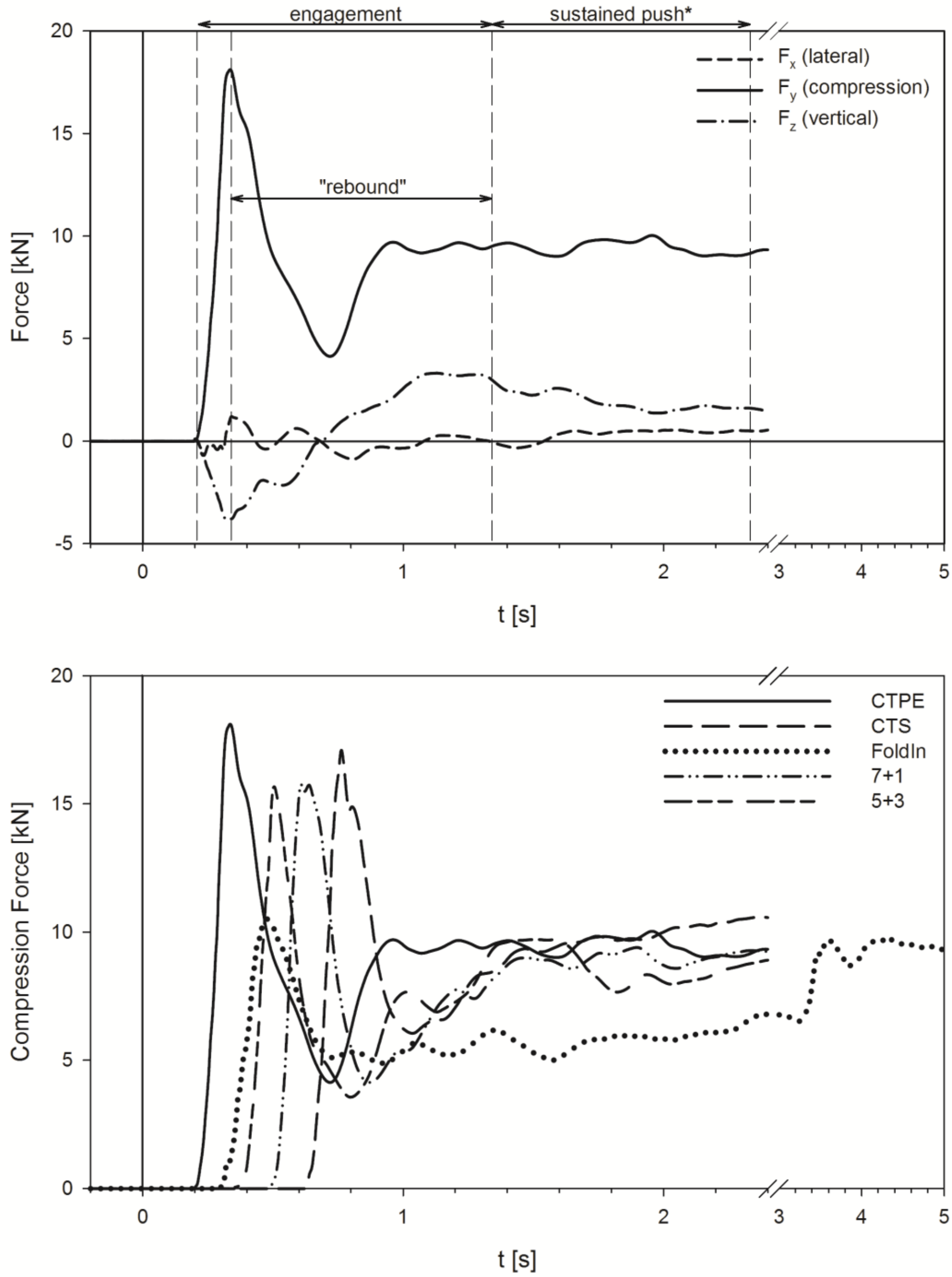

Figure 2. Example of the typical patterns of the three components of force in the CTPE technique (top), and of compression forces across the five different engagement procedures (bottom). The curves are taken from single trials of an International level team. The engagement phase is the interval between the onset of contact forces and 1 s after the peak of compression force; the sustained push phase is the 1 s interval from the end of engagament. *= given the different timing and number of referee calls, the sustained push for the Fold-in technique is the last 1 s.

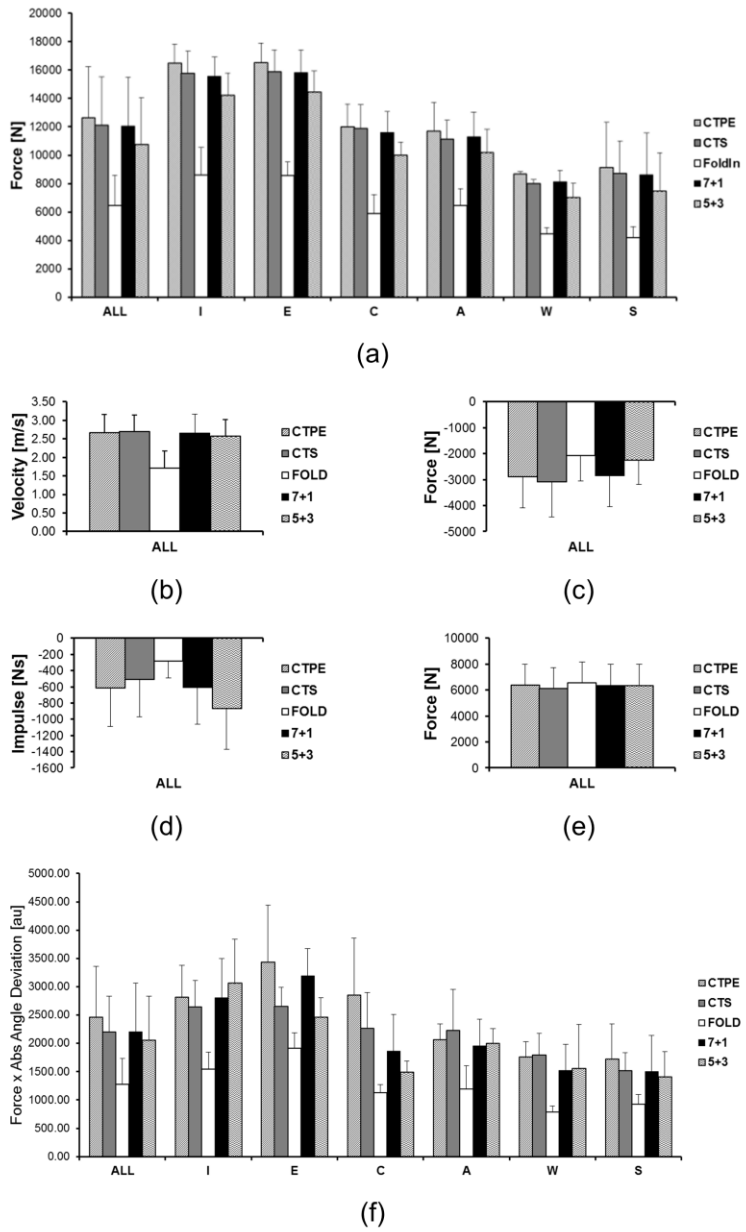

Figure 3. (a) Maximum compression force during the initial impact. (b) Engagement velocity. (c) Maximum vertical force during the initial impact (negative values mean downward force). (d) Negative impulse (i.e. loss of forward pushing ability) during the “rebound phase”. (e) Sustained push. (f) Maximum hazard measure during engagement. ALL= all playing levels together; I= International; E= Elite; C= Community; A= Academy; W= Women; S= School. The five different engagement techniques are reported in different colours. Values are reported as mean and standard deviation.